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PHOTONICS SPACE TIME PROCESSING

Pierre J. Talbot

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Rome Laboratory
Air Force Materiel Command
Rome, New York

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13. ABSTRACT *(Maximum 200 words)*

Radar clutter is usually characterized statistically by two parameter lognormal or Weibull models. The utilization of two parameter models has been impeded by a lack of methods for estimating the parameters. An optical monopulse chirp processor is presented that performs real-time adaptive estimates of the lognormal and Weibull parameters. The processor architecture requires only mature optical power or heterodyne spectrum analyzer technology. The optical monopulse chirp processor issued as United States Patent #5,546,089 on August 13, 1996.

14. SUBJECT TERMS
Optical monopulse chirp processor, real-time two-parameter clutter modeling, real-time CFAR threshold determination, monopulse clutter data collection, parallel optical channelization

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List of Figures page no.

I. Introduction [1]

CFAR (Constant False Alarm Rate) Detection schemes are routinely utilized in radar implementation to prevent saturation of processor target capacity by extraneous signals or clutter. Sections I and II present a brief summary of the CFAR problem and current electronic processing schemes that attempt to address the problem. The presentation abbreviates Minkler and Minkler's thorough discussion and isolates inadequacies in current technique that present opportunities for improvement through the utilization of optical processing techniques.

The motivating problem in CFAR detection can be simply stated : Given an **observation** (a sample magnitude) associated with a particular **cell** (location), make a determination as to whether a target is present in a clutter environment. A **target** is a statistical object - something you want to detect. **Clutter** is another statistical object - something you don't want to detect. The determination is usually made from a comparison of the sampled magnitude with a detection **threshold**. The detection threshold is selected so that it divides the probability distributions of the target and clutter environment "optimally". Figure 1 illustrates representative probability distributions for clutter and target. The probability distributions are assumed to overlap but essentially can be distinguished.

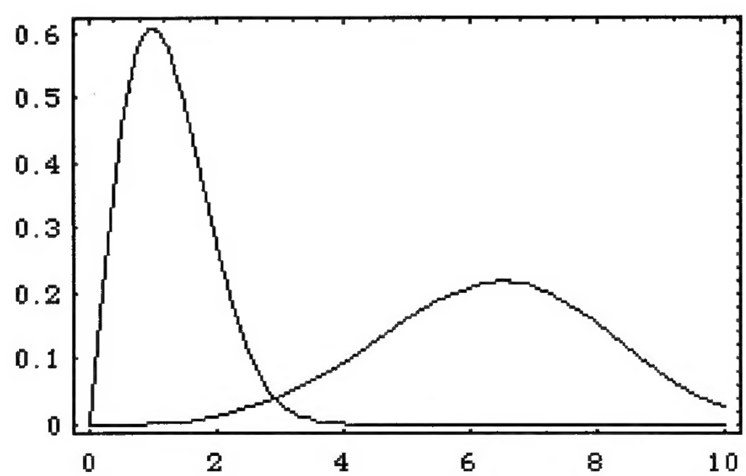

Figure 1. Statistical distribution of clutter and target magnitude return of radar.

Due to the overlap of probability distributions, the possibility for making mistakes in the detection process exists regardless of the threshold selected. Two types of detection errors are possible. A **Miss** occurs where you determine no target is present when a target is present. A **False Alarm** occurs where you determine a target is present when no target is present. An important radar parameter is the false alarm rate :

False Alarm rate: $\text{FAR} = \dfrac{\text{number of false alarms}}{\text{second}}.$

A substantial false alarm results in a significant capacity on post-detection radar processors. CFAR detection attempts to minimize and fix the false alarm rate by selecting the detection threshold based upon the probability of a false alarm. The probability of a false alarm is dependent only on the probability distribution of the clutter environment.

Probability of False Alarm : $P_{fa} = \int_{T}^{\infty} p_{D|clutter}(x)dx$

Conceptually the probability distribution of the clutter is assumed known, the probability of false alarm is specified and the appropriate threshold is determined. However, solving for T is not an easy problem in the simplest of cases! The probability of detecting a target given the calculated threshold can then be determined given the probability distribution of the target.

Probability of Detection : $P_d = \int_{T(P_{fa})}^{\infty} p_{D|target}(x)dx$

In order to appreciate the difficulty of calculating appropriate detection threshold, we can consider a number of cases of increasingly complex detection strategies and clutter environments.

Simple Case Example : single pulse detection / one parameter clutter model

$$T = E[D \mid \text{clutter}]\sqrt{\frac{4}{\pi}\ln\left(P_{fa}^{-1}\right)}$$

Note : 1. CFAR threshold is not dependent on target.
2. The mean clutter magnitude needs to be known.
3. Everything else is known or given.

Estimation of the mean clutter magnitude from a finite sample set affects the threshold expression. A complicated integral expression called the threshold coefficient must be calculated and substituted for the previous radical.

$$T = E'[D \mid \text{clutter}]C(P_{fa}, K)$$

Note : 1. How to estimate mean clutter magnitude in real time?
2. Computation of the **threshold coefficient** in the simplest case is horrible!

Harder Case Example : multiple pulse detection / one parameter clutter model

The utilization multiple pulse integration require the computation of an integral expression called the false alarm function which is dependent on the probability of false alarm.

$$T = E[D \mid \text{clutter}]\sqrt{\frac{\pi}{2}}\, g_n^{-1}(P_{fa})$$

Note : 1. CFAR threshold is not dependent on target.
2. The mean clutter magnitude needs to be known.
3. The computation of the **false alarm function** is horrible!

Again, estimation of the mean clutter magnitude from a finite sample set affects the threshold expression.

$$T = E'[D \mid \text{clutter}]C(P_{fa}, K)$$

Note : 1. How to estimate mean clutter magnitude in real time?

2. Computation of the new threshold coefficient is even worse!!

The two cases considered are actually relatively simple due to the assumption that the clutter environment can be described adequately utilizing a one parameter probability distribution. **However, one parameter probability models have been determined to poorly characterize most realistic clutter environments!** Another case will illustrate the complexity introduced if more realistic **two parameter clutter models** are assumed in the threshold determination.

Simple Case Example : single pulse detection / two parameter clutter model

$$T = x_m\left[\frac{\ln\left(P_{fa}^{-1}\right)}{\ln 2}\right]^{1/\alpha} = E[x]\frac{\left[\ln\left(P_{fa}^{-1}\right)\right]^{1/\alpha}}{\Gamma\left[1+(1/\alpha)\right]}$$

Note : 1. CFAR threshold is not dependent on target.

2. The mean clutter magnitude needs to be known.

3. The clutter **shape parameter** needs to be known.

4. Everything else is known.

Again, estimation of the mean clutter magnitude from a finite sample set affects the threshold expression

$$T = E'[D \mid \text{clutter}]C(P_{fa}, K, \alpha)$$

Note : 1. How to estimate mean clutter magnitude in real time?

2. Computation of threshold coefficient is dependent on the shape parameter and is still worse!!!

It is important to note that currently shape parameters are assumed and never estimated from data in real time!

II. Methods, Assumptions, and Procedures [1]

Current cell averaging implementation of CFAR detection for one and two parameter clutter models provide methods for adaptively estimating the clutter mean required in the threshold expressions presented in Section I. Implementing the mean clutter magnitude estimate and threshold determination in real time utilizes the calculation of clutter sample averages within a clutter window. Figure 2 illustrates the processing scheme for the simple case of single pulse detection utilizing a two parameter clutter model.

$$T = C(P_{fa}, K, \alpha)E^{'}[x] = C(P_{fa}, K, \alpha)\left(\frac{1}{K}\sum_{i=1}^{K} X_j\right)$$

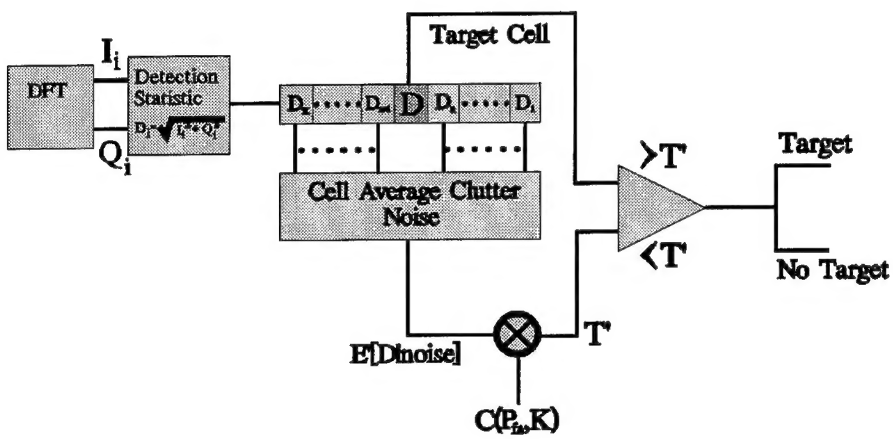

Figure 2. Cell Averaging CFAR detection.

Note : 1. Clutter mean is estimated using a **window** of resolution cell.

2. Small number of samples (32 or 64).

3. Clutter model is not determined (i.e. x_m and α unknown).

4. Threshold coefficient is a complicated value to compute.

5. Shape parameter is assumed known and constant.

6. The estimation process has introduced a type of "real-time adaptive thresholding".

The theoretical validity of the cell averaging implementation of CFAR detection is critically dependent on the accuracy of a number of assumptions regarding the clutter sample in the cell window.

Clutter model assumptions : Homogeneous clutter in averaging window.

1. Clutter model is constant over resolution cell space.
2. Clutter model is constant for sequential processing time.
3. Clutter samples from window cells are statistically independent.

The clutter model assumptions are required for the tractable derivation of all ideal and estimated forms of the threshold expressions for all combinations of detection strategy and statistical clutter models. Realistic clutter characteristics in the window are such that one or more of clutter model assumption can easily be violated. Clutter data collection in cell averaging consists of sampling clutter returns in sequential range/angle bins over time. It is assumed that no target is present in the cell averaging window. Figure 3 illustrates typical clutter characteristics encountered in the processing window.

Type of violations of the data collection constraints:

1. Target is present (large discreet).
2. Inhomogeneous clutter.
    a. time varying clutter (clutter edge).
    b. spatial variation in clutter (clutter edge).
3. Meaningless clutter returns (range inappropriate clutter sample).

Corrupted clutter data collection has fostered ill-founded and extremely complicated processing approaches with the goal of extracting the “true” clutter characteristics. Current cell averaging CFAR accommodations to real clutter characteristics attempt to determine violations to the clutter model assumptions and exclude inappropriate clutter samples from the sample average utilized to estimate the clutter mean. Figures 4 and 5 illustrate the type of implementation accommodation that are standard fixes for non-ideal clutter windows.

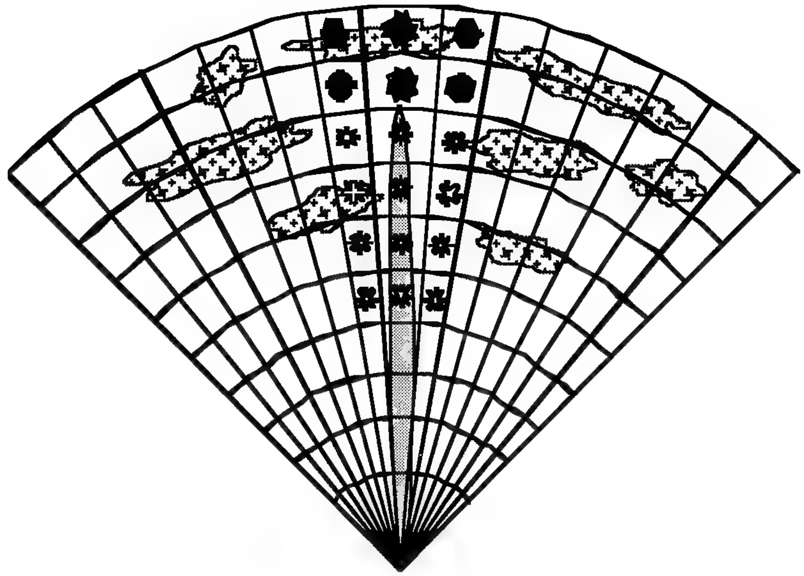

Figure 3. Cell averaging window in current CFAR schemes.

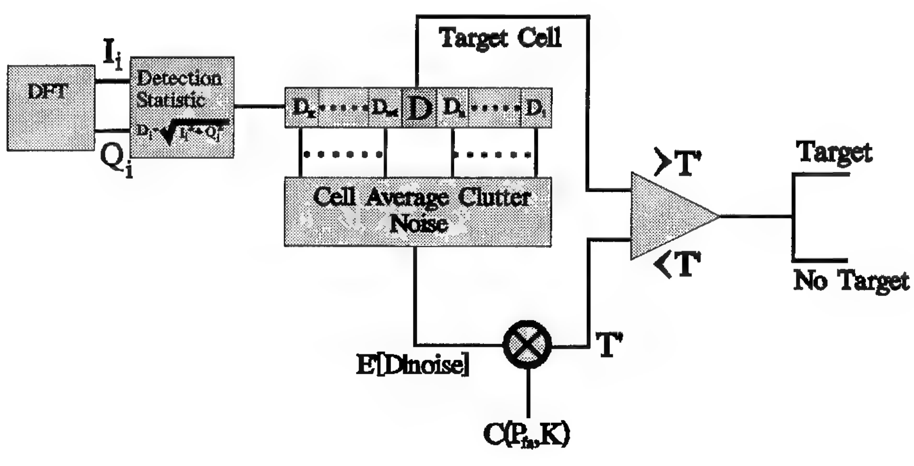

Figure 4. Cell Averaging CFAR in homogenous clutter window.

A clutter edge fix is typically implemented by dividing the clutter window and selecting the half-window most appropriate in calculating the clutter sample average.

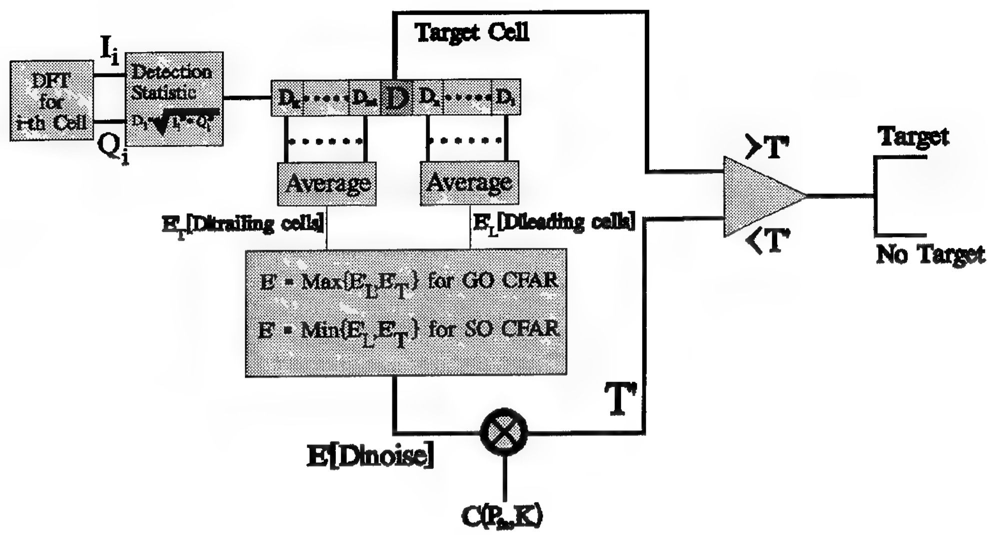

Figure 5. Cell Averaging CFAR in non-homogenous clutter window.

Note : 1. Clutter mean is estimated using a **subwindow** of resolution cells. "Adaptive" in clutter mean.

2. **Heuristic decision** making in clutter characterization prior to detection decision.

3. Smaller number of samples (16 or 32).

4. Clutter model is not determined (i.e. x_m and α unknown).

5. Threshold coefficient is a complicated value to compute.

6. Shape parameter is assumed known and constant. Non-adaptive in shape parameter

Extensions of this approach to **order statistics (OS CFAR)** leads to accommodations for **large discrete** and **non-centered equal-sized clutter partitions**.

Many other alternative approaches have been suggested and utilized :

1. **log-t detector** : brut force determination of clutter mean and variance followed by transformation normal clutter distribution for large number of samples.

2. **non-parametric detectors** : lots of complicated computation, lots of data needed, requires unrealistic assumptions about clutter.

3. other **"embedded" CFAR processor** : even more complicated computation, haven't spent much time reviewing claims and assumptions here.

Most approaches accepted as useful in a limited range of situations.

4. consequently, the "lets use expert systems" trend. Not only within a particular approach but also in choosing an approach initially.

This brief survey allows for some general observation regarding the current state-of-the-art in cell averaging CFAR. We can also more clearly see what would constitute an ideal real-time CFAR processing capability.

What we have now (what we would like to have) :

1. "Corrupted" real-time adaptation to homogeneous window clutter mean ("true" real-time adaptation heterogeneous two parameter clutter model).
2. Clutter mean determination (clutter two parameter determination).
3. Lots of computation, data, assumptions, and decision making (minimal computation, data, assumptions, and decision making).

III. Results and Discussion [3]

The **Optical Monopulse Chirp Processor** is a patented detector design that resulted from the previously unrecognized combination of monopulse techniques, two-parameter clutter models, and optical channelization techniques. The optical monopulse chirp processor provides a simple processing alternative to current CFAR detectors. In addition, it provides a significantly closer approximation to the ideal real-time adaptive two-parameter clutter model CFAR capabilities outlined in Section II.

Single chirped monopulse clutter data collection is the foundation to the processors capabilities. The novel paradigm for monopulse clutter data collection requires the parallel processing capability provided by simple and well established optical techniques for real-time implementation. Figure 6 illustrates the principle of monopulse chirp clutter data sample collection.

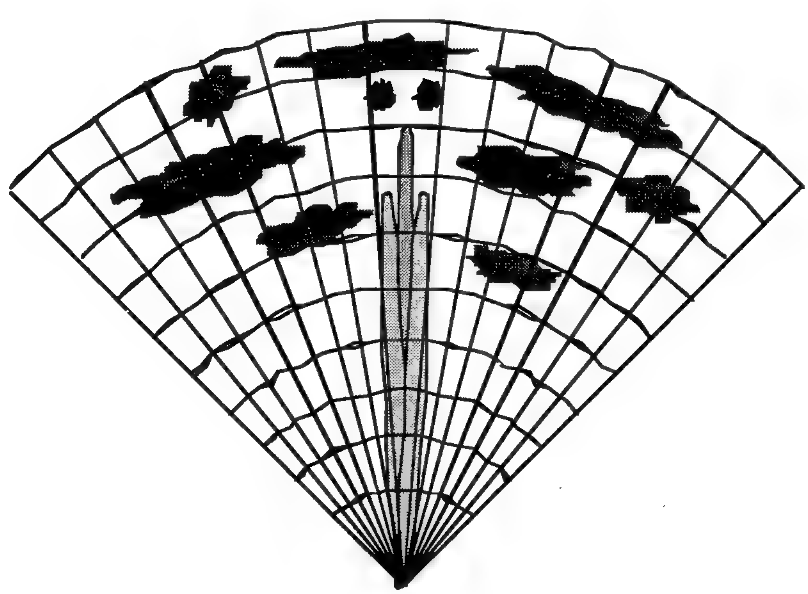

Figure 6. Optical monopulse chirp processor clutter window.

Two significant characteristics of monopulse clutter data collection can be identified :

1. Clutter data collected only in **"monopulse range/angle cell"** of interest.
2. Chirped pulse provides large number of **frequency decorrelated** clutter samples.

In addition the **sum and difference beam** inputs required of the Optical Monopulse Chirp Processor are already available from any current **monopulse tracking systems** for targets.

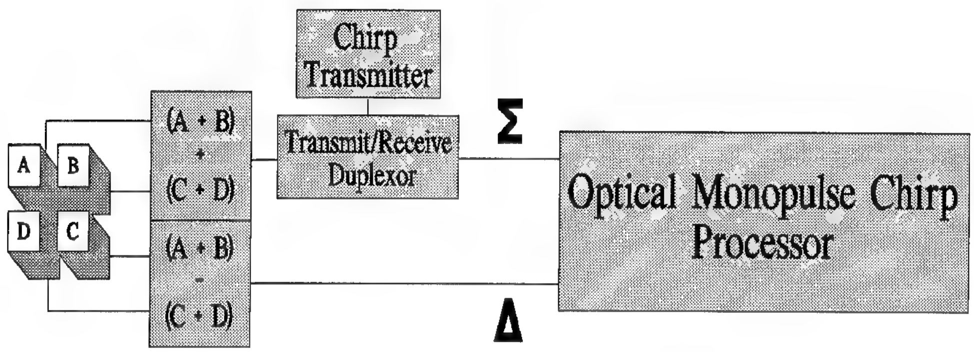

Figure 7. Processor integration into existing monopulse radar.

The sum and difference beam clutter returns can be represented as the sum and difference of random variables characteristic of the clutter probability distribution.

Sum Beams : $X_\Sigma = X_A + X_B + X_C + X_D$.

Difference Beam : $X_\Delta = X_A + X_B - X_C - X_D$.

Expected values are not a natural quantity to consider for monopulse target returns; but for clutter returns you get something remarkable!

$$\boxed{E[X_\Sigma] = 4\mu}$$

$$\boxed{E[X_\Delta^2] = 4\sigma^2}$$

The expected values simultaneously provide the mean and variance of the clutter probability distribution.

$$\text{Clutter mean}: \ \mu = \frac{E[X_\Sigma]}{4}$$

$$\text{Clutter Variance}: \ \sigma^2 = \frac{E[X_\Delta{}^2]}{4}$$

The utilization of a frequency chirp provides a large number of frequency decorrelated clutter sample that may be utilized in calculating accurate sample averages of the sum and difference random variable in the expression for the mean and variance of the clutter probability distribution

$$\mu \cong \mu_{freq} = \frac{1}{4K} \sum_{i=1}^{K} X_\Sigma(f_i)$$

$$\sigma^2 \cong \sigma_{freq}{}^2 = \frac{1}{4(K-1)} \sum_{i=1}^{K} X_\Delta{}^2(f_i)$$

Parallel optical channelization of the chirp clutter return is implemented utilizing either power or heterodyne optical spectrum analyzers [2]. An optical implementation of the clutter data collection and sample average calculations provide real-time adaptive two-parameter clutter determination. Figure 8 illustrates the optical monopulse chirp processor architecture implemented with a power spectrum analyzer.

Optical Monopulse Chirp Processor

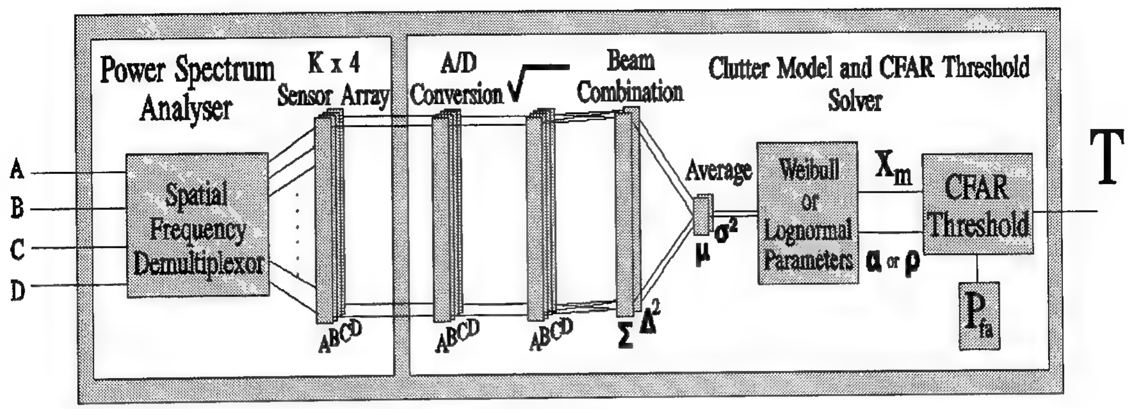

Figure 8. Optical monopulse chirp processor.

Given the estimated mean and variance of the clutter model probability distribution, the solution of two simultaneous equations provides the clutter model parameters.

$$E[x] = e^{b + a^2/2}$$

$$Var[x] = e^{2b + a^2}\left(e^{a^2} - 1\right)$$

Solving for the model parameter give :

$$a = \sqrt{\ln\left(\frac{Var[x]}{E^2[x]} + 1\right)}$$

$$b = \ln\left(\frac{E[x]}{e^{a^2/2}}\right)$$

The clutter model, that is the parameters, and the ideal CFAR threshold are immediately available without complicated integral calculation as in previous cell averaging CFAR estimation techniques.

$x_m = b$ (the "median" parameter)

$\rho = e^{a^2/2}$ (the "shape" parameter)

$$T = x_m e^{\sqrt{4 \ln \rho}\, \mathrm{erf}^{-1}(1 - 2P_{fa})}$$

Note : 1. Clutter mean and variance are estimated for the resolution cell of interest.

2. Large number of samples.

3. Clutter model is determined (i.e. x_m *and* ρ are determined)

4. Threshold is calculated simply and directly from clutter model parameters.

The clutter model assumptions for the optical monopulse chirp processor are actually much more realistic than the standard assumption required of cell averaging CFAR techniques.

Optical Monopulse Chirp Processor Clutter model assumptions :

1. Homogeneous clutter model over spatial extent of four beams in monopulse - "smaller window".
2. Independent clutter samples returned from the spatially separated four beams of monopulse.

IV. Conclusions

Real-time two-parameter radar clutter modeling is now practical in radar remote sensing and target detection environments. An optical implementation of the monopulse chirp processor has been presented that provides for the real-time estimation of the clutter variance as well as the clutter mean. The estimated clutter mean and variance allow the calculation of both lognormal and Weibull clutter model parameters. The requirement of a homogeneous clutter model over a single resolution cell during a single chirped radar pulse is a more realistic condition than the homogeneous clutter window requirements of current cell averaging CFAR processors. The optical monopulse chirp processor could be easily integrated into existing traditional monopulse tracking and modern multiple beam forming phased array systems.

V. Recommendations

An experimental proof-of-concept demonstration of the processing principles that form the basis for the patented Optical Monopulse Chirp Processor design will be conducted, recorded, and ultimately reported in a second experimentally oriented sequel to the original refereed journal report of the processor design by Dr. Talbot. The experimental demonstration will implement the OMCP utilizing power and heterodyne optical spectrum analyzers. Initially, realistic clutter data set will be simulated to ease verification of the implementation's operation. Two-parameter clutter return data sets will be developed in Mathematica and down-loaded to the HP FASS System for signal generation. If time permits, real clutter data sets could be acquired and assayed as an ultimate test of the OMCP's capabilities.

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Appendix : Patent

United States Patent [19]

Talbot

[11] **Patent Number: 5,546,089**

[45] **Date of Patent: Aug. 13, 1996**

[54] **OPTICAL MONOPULSE CHIRP PROCESSOR**

[75] Inventor: **Pierre J. Talbot**, Alder Creek, N.Y.

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **513,369**

[22] Filed: **Aug. 10, 1995**

[51] **Int. Cl.**^{6} **G01S 7/292**; G01S 7/34

[52] **U.S. Cl.** **342/159**; 342/162; 342/93; 342/192

[58] **Field of Search** 342/159, 162, 342/52, 54, 93, 192

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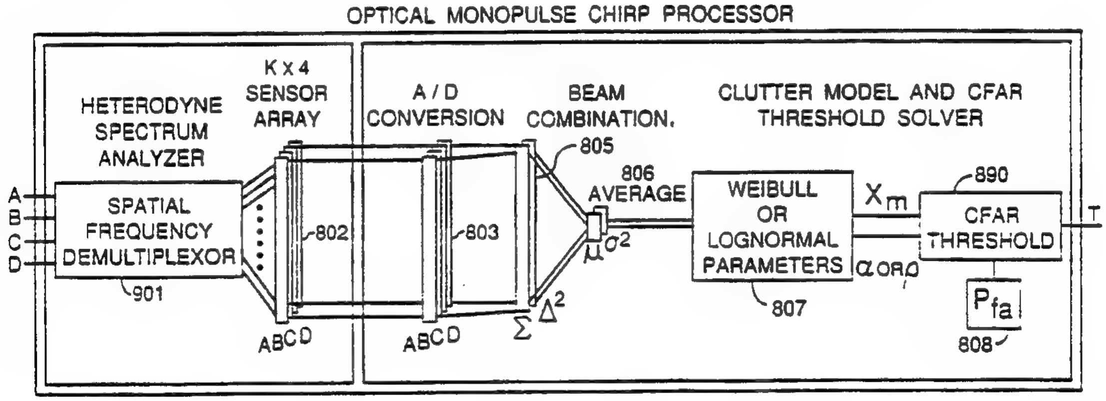
Primary Examiner—John B. Sotomayor
Attorney, Agent, or Firm—William G. Auton

[57] **ABSTRACT**

An optical chirp processor for the collection and processing clutter samples is presented that allows the simultaneous estimation of both the clutter mean and variance.. The estimated clutter mean and variance allow the actual calculation of both clutter model parameters using a power spectrum analyzer, and a CFAR special purpose processor unit. The power spectrum analyzer is composed of: a spatial frequency demultiplexor, and a four element photodetector array. The special purpose processor is composed of: an A/D converter, a square root calculator, an averaging calculator, a combiner unit, a parameter memory unit, and a threshold calculator unit. The components of the CFAR processor may be implemented in a conventional CFAR processor (when modified by the teachings of the present invention) or in individual electronics components.

12 Claims, 4 Drawing Sheets

OPTICAL MONOPULSE CHIRP PROCESSOR



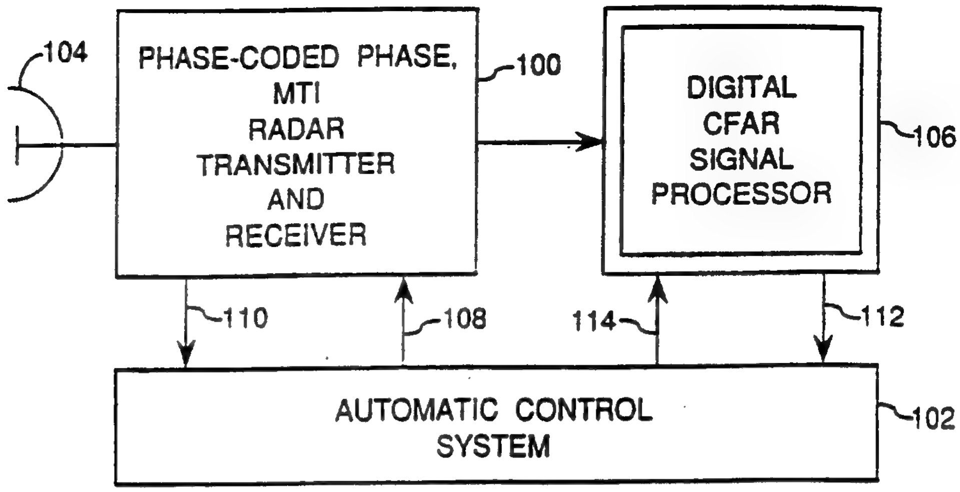


FIG. 1

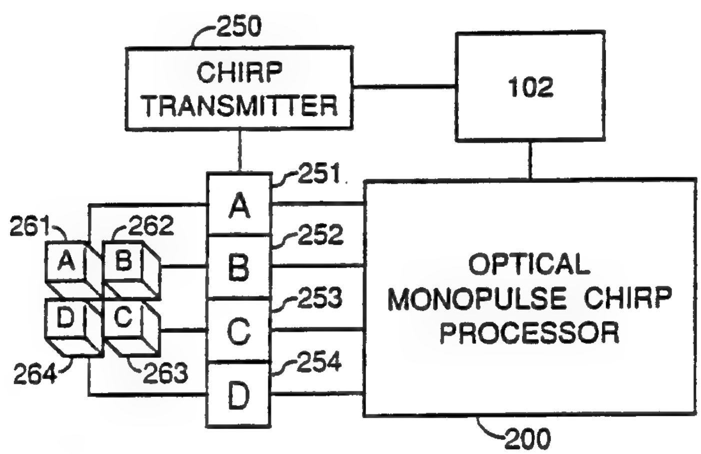


FIG. 2

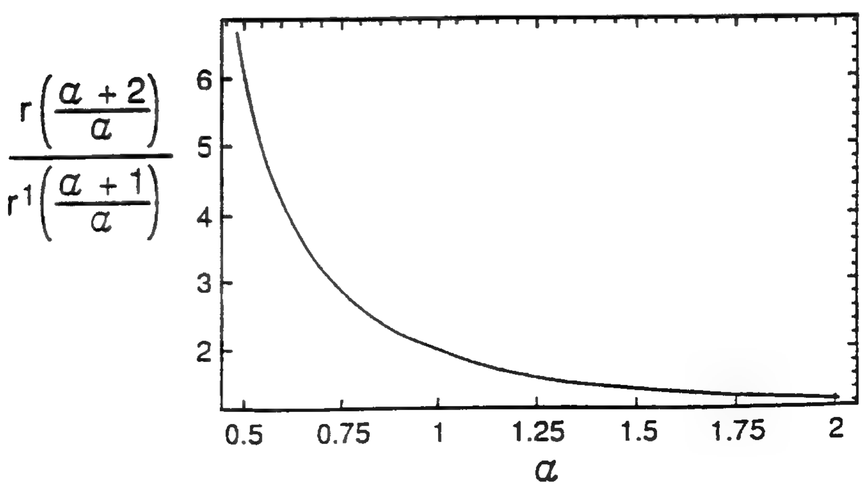


FIG. 3

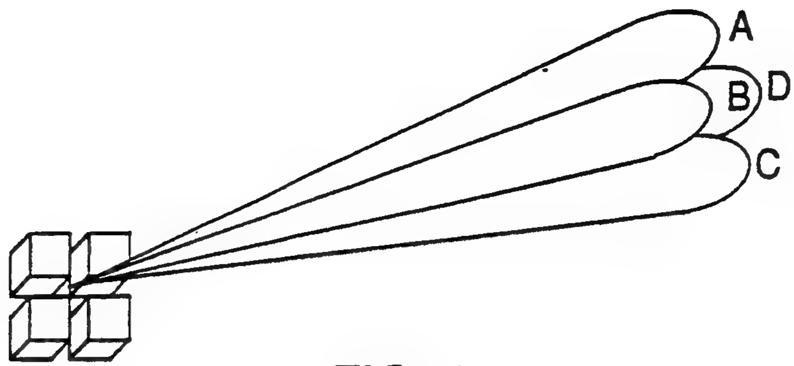


FIG. 4

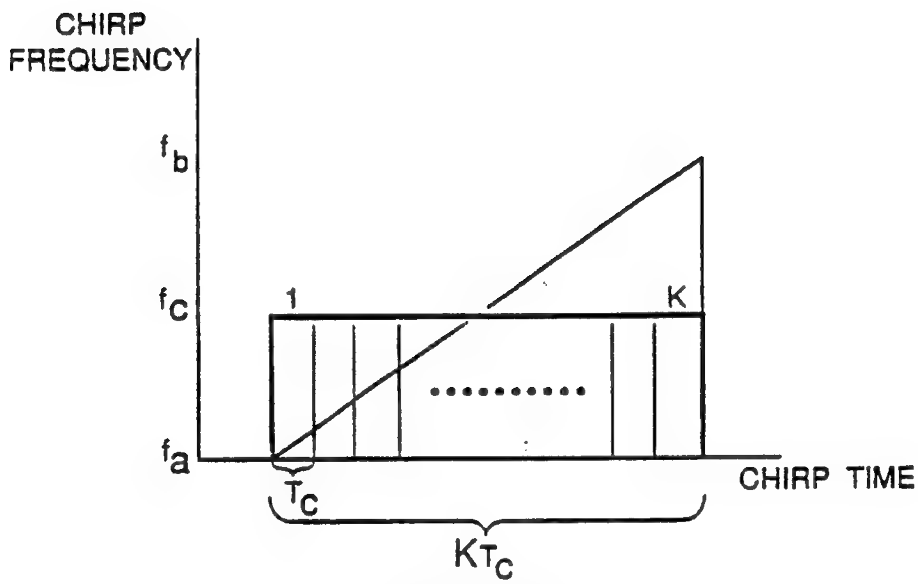


FIG. 5

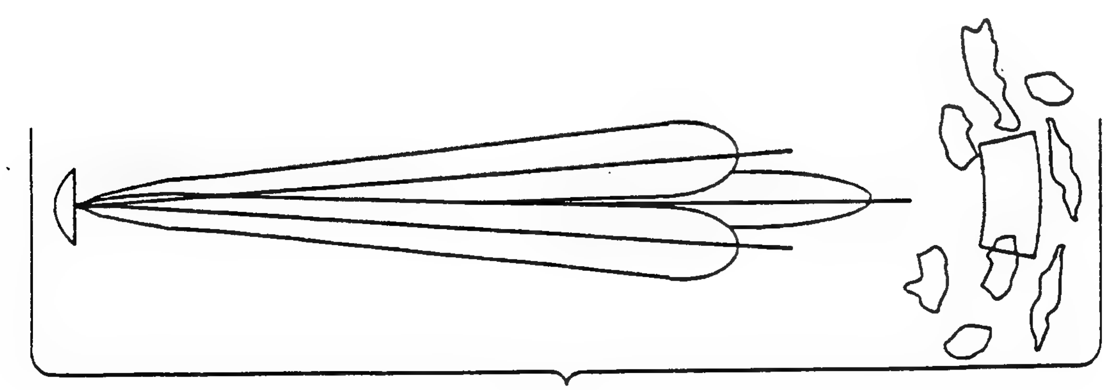


FIG. 6

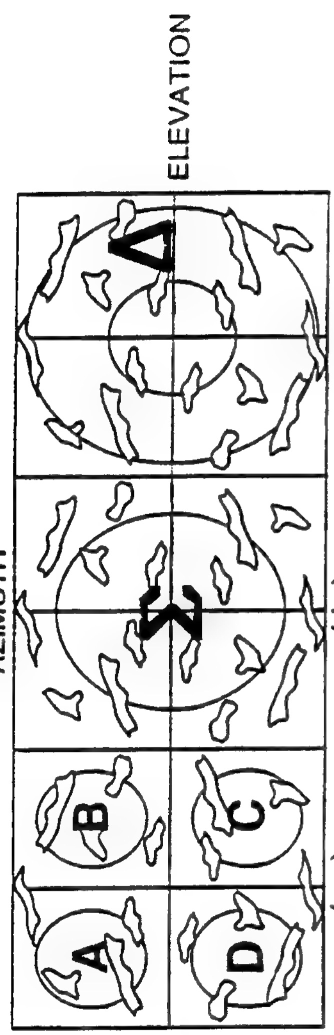

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FIG. 7

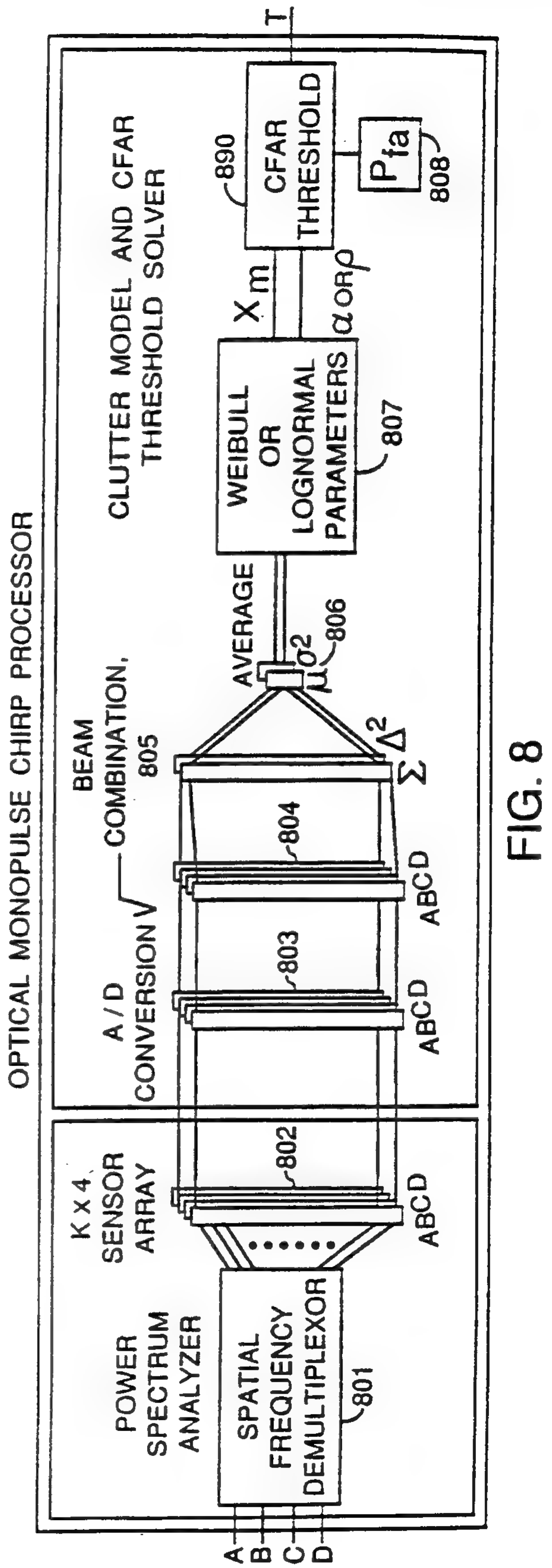
OPTICAL MONOPULSE CHIRP PROCESSOR
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FIG. 8

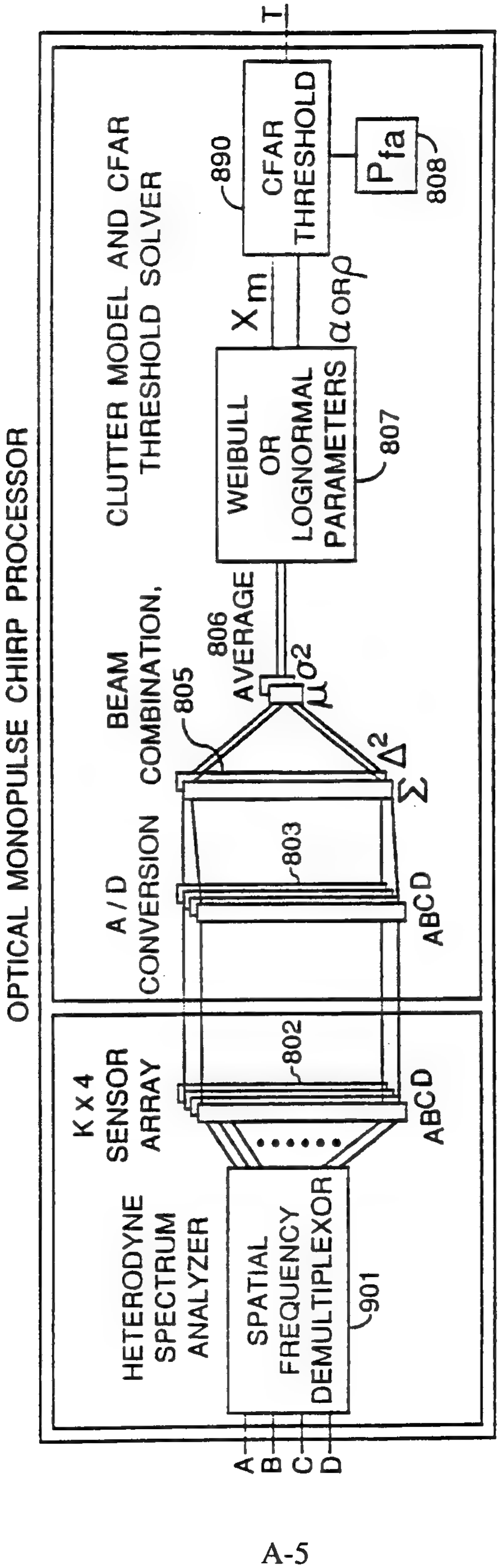
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FIG. 9

OPTICAL MONOPULSE CHIRP PROCESSOR

OPTICAL MONOPULSE CHIRP PROCESSOR STATEMENT OF GOVERNMENT INTEREST

The invention described herein may be manufactured and used by or for the Government for governmental purposes without the payment of any royalty thereon.

BACKGROUND OF THE INVENTION

Constant false alarm rate (CFAR) techniques are frequently utilized in radar receivers to prevent saturation of radar target detection and tracking processors. Target detection is a statistical process and as such requires an accurate characterization of target and clutter statistics for the determination of an optimal CFAR detection threshold. CFAR techniques rely on the adaptive update of receiver detection thresholds to maintain a constant probability of false alarm. The detection threshold must be adaptively updated to accommodate variations in the radar clutter background. Two parameter statistical models are generally required to accurately characterize radar clutter for a wide range of clutter types and conditions. The most commonly utilized clutter models include the lognormal and the Weibull statistical distributions. An accurate description of radar clutter utilizing either of these statistical distributions amounts to the determination of the two model parameters.

The utility of these two parameter models has been limited by a lack of methods for estimating the parameters. Currently, practical CFAR techniques consist of radar resolution cell averaging schemes for the estimation of the clutter mean. These cell averaging schemes utilize an estimated clutter mean and empirically established values of the model "shape" parameter associated with the clutter type to set a detection threshold. In addition, the utilization of clutter mean estimates and the estimation of clutter means from a finite number of clutter samples requires the computation of complex threshold coefficients in the determination of a detection threshold. Inaccuracies in the determination of the clutter mean result in cell averaging CFAR threshold that are larger than the optimal values. The cell averaging CFAR thresholds result in a reduction in the probability of target detection. Ideally, it would be desirable to calculate optimal CFAR thresholds directly from known clutter model parameters. Aspects of the current state-of-the-art in cell averaging CFAR in traditional radar processors are briefly described in the following U.S. Patents, the disclosures of which are incorporated herein by reference:

U.S. Pat. No. 4,586,043 issued to Mary Wolf;

U.S. Pat. No. 4,532,639 issued to Price et al;

U.S. Pat. No. 4,513,286 issued to Irabu;

U.S. Pat. No. 4,293,856 issued to Chressanthis;

U.S. Pat. No. 4,103,301 issued to Evans;

U.S. Pat. No. 3,995,270 issued to Perry et al;

U.S. Pat. No. 3,968,490 issued to Gostin; and

U.S. Pat. No. 3,701,1498 issued to Patton et al.

The above-cited patents all describe radar CFAR processors. Monopulse techniques provide standard methods of accurate angular positioning in radar tracking systems. There remains a need for a monopulse scheme for the collection and processing of clutter samples is presented that allows for the simultaneous estimation of both the clutter mean and variance. The estimated clutter mean and variance should allow the calculation of both clutter model parameters. Knowledge of the clutter model parameters should allow for a simple calculation of the optimal CFAR detection threshold. The present invention is intended to satisfy these needs.

SUMMARY OF THE INVENTION

The present invention is a special purpose monopulse chirp processor that performs real-time adaptive estimates of CFAR detection thresholds for radar tracking systems using a power spectrum analyzer, and a CFAR special purpose processor unit. The power spectrum analyzer is composed of:

a spatial frequency demultiplexor, and a four-element photodetector array. The special purpose processor is composed of:

an A/D converter, a square root calculator, and averaging calculator, a combiner unit, a parameter memory unit, and a threshold calculator unit. The components of the CFAR processor may be implemented in a conventional CFAR processor (when modified by the teachings of the present invention) or in individual electronics components. In operation, the power spectrum analyzer receives sum and difference beam clutter cross sections collected from at least four beams of a phased array radar antenna and receiver system. The power spectrum analyzer outputs four electric signals that represent the square of the clutter returns using the spatial frequency demultiplexor (which separates and processes the four beam in parallel) and the four element sensor array (which converts the four optical output beams of the spatial frequency demultiplexor into their four equivalent transverse electrical signals by photodetecting received optical beams. The A/D converter outputs four digital data streams by processing the four electrical signals from the sensor array. The square root calculator calculates the square root of each of these four digital data streams to produce thereby four digital clutter return measurement signals. The beam combiner combines the four digital clutter return measurement signals for averaging and CFAR detection threshold calculation as described in the above-cited patent of Mary Wolf.

As described in the Wolf patent:

Once the X average clutter value is know, for a Rayleigh distribution estimate of threshold is given by:

$$T=(-LNP)^{1/2}\cdot\frac{2X}{\sqrt{\pi}}.$$

If the distribution is Weibull,

$$T=b-\frac{(LNP)}{(a)}$$

The selection of which estimation method is desired is implemented by the parameter memory unit and CFAR processor.

It is an object of the present invention to provide real-time CFAR detection thresholds for phased array radar systems.

It is another object of the present invention to provide a design for a special purpose optical chirp processor.

These objects together with other objects, features and advantages of the invention will become more readily apparent from the following detailed description when taken in conjunction with the accompanying drawings wherein like elements are given like reference numerals throughout.

DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a radar system in which the optical CFAR signal processor of the present invention may

be deployed:

FIG. 2 is an illustrative block diagram of the optical CFAR signal processor of the present invention:

FIG. 3 is a chart of Gamma function ratio as a function of the Weibull shape parameter:

FIG. 4 is an illustration of four monopulse beams emitted by the four elements of FIG. 2;

FIG. 5 is a chart of Single clutter resolution cell of monopulse sum and difference beams:

FIG. 6 is a side view of the four beams of FIG. 4 directed from an array to a target:

FIG. 7 is an illustration of resolution cell beam combination for: a) Individual monopulse beams, b) Sum beam, c) Difference beam

FIGS. 8 and 9 are detailed illustrations of an optical monopulse chirp processor used with radar systems respectively for Power spectrum analyzer implementation, and Heterodyne spectrum analyzer implementation.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The present invention is a special purpose monopulse chirp processor that performs real-time adaptive estimates of the lognormal and Weibull parameters and CFAR thresholds.

Radar clutter is usually characterized statistically by two parameter lognormal or Weibull models. Knowledge of the parameters allows the calculation of detection thresholds in implementing adaptive CFAR receivers. The utilization of two parameter models has been impeded by a lack of methods for estimating the parameters. Presently, CFAR techniques avoid two parameter threshold calculations sand instead rely upon cell averaging schemes that are based upon knowledge of the clutter mean. An optical monopulse chirp processor of the present invention performs real-time adaptive estimates of the lognormal and Weibull paramets and CFAR thresholds.

FIG. 1 is a block diagram of a radar system in which the optical CFAR signal processor of the present invention may be deployed. The system of FIG. 1 includes a phase-coded pulse. MTI radar transmitter and receiver **100**, automatic control system **102**, scanning antenna **104** and digital CFAR signal processor **106**. Automatic control system **102** applies required control signals to radar **100** over interconnection **108**, while radar **100** feeds back data signals to automatic control system **102** over interconnection **110**. Similarly, automatic control system **102** applies control signals to processor **106** over interconnection **112** and processor **106** feeds back data signals to automatic control system **102** over interconnection **114**.

Among the control signals applied to radar **100** from automatic control system **102** over interconnections **108** is a selected serial phase code composed of a predetermined plural number of bits. This predetermined number is equal to or less than a given number 11.

As is known in the radar art, scanning antenna **104** receives echoes of each successive exploratory pulse reflected from targets and also receives some quantity of noise and possibly clutter. As is conventional, the radar receiver includes a front-end, an IF amplifier and a baseband detector. Further, the radar receiver normally is gated by a range gate which is open during a given range interval (selected by control signals from automatic control system **102**), for forwarding to the baseband detector only those target echoes which occur during the given range interval. The size of the given range interval (determined by the width of the range gate) is normally dependent upon the maximum range of detection for a given dwell.

The output of the baseband detector of the receiver of radar **100** is applied as an input to digital CFAR signal processor **106**. In general, processor **106** includes an MTI canceller, which operates as a bandpass doppler-frequency filter that removes substantially all stationary and slow-moving target signals and also removes substantially all low-frequency noise and clutter present in the output of the baseband detector. The output of the MTI canceller, beside including moving target signals of interest, also includes that portion of the noise and clutter which is within the effective pass-band of the MTI canceller. The MTI canceller is mode dependent.

Included in the control signals applied to processor **106** from automatic control system **102** over interconnection **114** is the same selected serial phase code that is then being used to phase-modulate the transmitted exploratory pulses. Processor **106** also includes a threshold comparator for comparing the output level from the discrimination means to a variable threshold level applied to a processor **106** from automatic control system **102** over interconnection **114**. The threshold level is varied in such a manner that an output from the threshold comparator (which applies a data signal to automatic control system **102** over interconnection **112**) corresponds to a preselected constant false alarm rate (CFAR). The higher the degree of discrimination of the discrimination means of processor **106**, the lower is the absolute level of the threshold required to provide a certain CFAR. Further, the lower the absolute level of the threshold, the less is the effective reduction in sensitivity of the radar receiver, compared to that of an optimum-matched receiver.

FIG. 2, a four-element monopulse radar system that emits four beams through elements **261–264** from a transmitter **250**, and electronically steered by phase shifter **251–254** as controlled by a processor **200**. Radar echo return signals that include both target echos and clutter signals are received by the elements **261–264** and conducted into the processor **200**.

The most commonly utilized clutter models include the lognormal and the Weibull statistical distributions. An accurate description of radar clutter utilizing either of these statistical distributions amounts to the determination of the two model parameters.

The utility of these two parameter models has been limited by a lack of methods for estimating the parameters. Currently, practical CFAR techniques consist of radar resolution cell averaging schemes for the estimation of the clutter mean. These cells averaging schemes utilize an estimated clutter mean and empirically established values of the model shape: parameter associated with the clutter type to set a detection threshold. In addition, the utilization of clutter mean estimates and the estimation of clutter means from a finite number of clutter samples requires the computation of complex threshold coefficients in the determination of a detection threshold. In addition, the utilization of clutter mean estimates and the estimation of clutter means from a finite number of clutter samples requires the computation of complex threshold coefficients in the determination of a detection threshold. Inaccuracies in the determination of the clutter mean result in cell averaging CFAR threshold that are larger than the optimal values. The cell averaging CFAR thresholds result in a reduction in the probability of target detection. Ideally, it would be desirable to calculate optimal CFAR thresholds directly from known

clutter model parameters. Aspects of the current sate-of-the-art in cell averaging CFAR in traditional radar processors are briefly described in the patents cited above.

Monopulse techniques provide standard methods of accurate angular positioning in radar tracking systems. The present invention provides a novel monopulse scheme for the collection and processing of clutter samples is presented that allows for the simultaneous estimation of both the clutter mean and variance. The estimated clutter mean and variance allow the calculation of both clutter model parameters. Knowledge of the clutter model parameters allow for a simple calculation of the optimal CFAR detection threshold. The monopulse scheme utilized frequency agility to collect a large number of independent clutter samples for an accurate estimation of the clutter mean and variance. The clutter samples are collected only from the single: radar resolution cell of interest. The collection of clutter samples from a single radar resolution cell during a single frequency chirped radar pulse eliminates the possibility of the clutter edge effects and large discrete interference that plague cell averaging CFAR techniques.

Two optical implementations of the monopulse chirp processor are presented in section four. Optical implementations are required for the practical collection of the large number of clutter samples required in accurately estimating the clutter mean and variance. The implementations require only optical power or heterodyne spectrum analyzers for the spatial demultiplexing of radar clutter returns from a chirped pulse. Optical spectrum analyzers are the most mature and easily implemented of optical signal processing technologies. The optical heterodyne spectrum analyzer implementation provide for the processing of clutter returns having a significant dynamic range. The optical monopulse chirp processor requires only the four beam responses comprising the sum and difference beams in traditional monopulse tracking systems.

In order to understand the principles of the present invention, consider the following. Radar clutter is usually characterized statistically by two parameter lognormal or Weibull models. Knowledge of the parameters allows the calculation of detection thresholds in implementing adaptive CFAR receivers. CFAR receivers maintain a constant false alarm rate by employing an adaptive threshold that ensures a fixed probability of false alarm given variation in the clutter model. The lognormal model of clutter has a probability distribution given by:

$$f(x)=\begin{cases}\dfrac{1}{x\sqrt{4\pi\ln\rho}}e^{-(\ln x-\ln x_m)^2/4\ln\rho} & x\geq 0\\ 0 & x<0\\ \text{or} & \\ \dfrac{1}{ax\sqrt{2\pi}}e^{-(\ln x-b)^2/2a^2} & x\geq 0\\ 0 & x<0\end{cases}\tag{1}$$

where

$b=x_m$ (the "median" parameter)

$a=\sqrt{2\ln\rho}$

$\rho=e^{a^2/2}$ (the "shape" parameter).

The mean and variance of the lognormal probability distribution can be expressed as functions of the model parameters.

$$E[x]=e^{b+a^2/2}\tag{2}$$

$$Var[x]=e^{2b+a^2}(e^{a^2}-1)\tag{3}$$

Knowledge of the mean and variance of the clutter allow the calculation of the two parameters of the lognormal model.

$$a=\sqrt{\ln\left(\frac{Var[x]}{E^2[x]}+1\right)}\tag{4}$$

$$b=\ln\left(\frac{E[x]}{e^{a^2/2}}\right)\tag{5}$$

The calculation of the optimal (i.e. minimal) CFAR threshold depends upon the type of detection strategy employed by the receiver. For example, given the parameter of the lognormal clutter model, the optimal CFAR threshold of single pulse linear detection receiver can be computed as a function of the required probability of false alarm and the model parameters.

$$T=x_m e^{\sqrt{4\ln\rho}\,erf^{-1}(1-2P_{fa})}=\frac{E[x]}{\rho}e^{\sqrt{4\ln\rho}\,erf^{-1}(1-2P_{fa})}\tag{6}$$

The optimal CFAR threshold is the minimum value consistent with the requirement of a specific constant probability of false alarm. The probability of detection is maximized for the optimal CFAR threshold. Similar CFAR threshold expressions have been determined for multiple pulse linear detection receivers and binary detection receivers. The threshold expressions for the various detection schemes can all be expressed as functions of the probability of false alarm and the lognormal model parameters.

Cell averaging techniques are frequently utilized to determine the CFAR threshold from an estimated clutter mean. The threshold estimate can be expressed as the product of the estimated clutter mean and a threshold coefficient.

$$T=C(P_{fa},K,\rho)E[x]=C(P_{fa},K,\rho)\left(\frac{1}{K}\sum_{i=1}^{K}x_i\right)\tag{7}$$

The clutter mean is estimated from the radar cross section response from a window of range/angle resolution cells surrounding the cell of interest. The clutter model for the cells comprising the average is assumed to be fixed for the duration of the radar response collection within the window. In addition, the clutter samples used in estimating the mean are assumed to be independent and homogeneous in space and time within the cell averaging window. If this condition is not met then clutter edge and large discrete effects may degrade the estimation of the clutter mean. In practice, processing speed and the requirement of a homogeneous clutter model within the window limit the number of cells in the average to sixty-four and in the majority of implementations to thirty-two. The cell averaging CFAR threshold estimates are greater than the optimal CFAR threshold due to inaccuracies in estimating the clutter mean from a finite number of samples. Consequently, the probability of detection is reduced for a fixed signal power to clutter power ratio. The increase in signal to clutter ratio required to maintain the probability of detection for finite clutter sample estimates of the CFAR threshold is known as CFAR loss. The threshold coefficient is generally a complicated and intractable function of the required probability of false alarm, the lognormal model shape parameter, and the number of samples used in estimating the clutter mean. In addition, the shape parameter of the lognormal model Of the actual clutter is unknown and values are utilized that have been determined as characteristic of particular types of clutter from previous CFAR receiver performance. However, as the number of indepen-

dent clutter samples in the estimate of the clutter mean increases, the threshold coefficient approaches the theoretical minimum.

$$C(P_{fa},K,\rho) \rightarrow \frac{1}{\rho} e^{\sqrt{4\ln\rho}\ \mathrm{erf}^{-1}(1-2P_{fa})} \quad \text{as } K \rightarrow \infty \tag{8}$$

A similar development is possible for the two parameter Weibull model. The analogous expressions for the probability distribution, the mean and variance, the model parameters, and the CFAR threshold can be given.

$$f(x) = \begin{cases} \dfrac{\alpha \ln 2}{x_m}\left(\dfrac{x}{x_m}\right)^{\alpha-1} e^{-\ln 2 (x/x_m)^{\alpha}} & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{9}$$

where

Xm (the "median" parameter)

α(the "shape" parameter).

$$E[x] = \frac{x_m}{(\ln 2)^{1/\alpha}}\,\Gamma\left(\frac{\alpha+1}{\alpha}\right) \tag{10}$$

$$Var[x] = \left(\frac{x_m}{(\ln 2)^{1/\alpha}}\right)^2\left[\Gamma\left(\frac{\alpha+2}{\alpha}\right) - \Gamma^2\left(\frac{\alpha+1}{\alpha}\right)\right] \tag{11}$$

The shape parameter for the Weibull model cannot be expressed in closed form but must be determined through the solution of an equation involving gamma functions.

$$\left[\frac{\Gamma\left(\frac{\alpha+2}{\alpha}\right)}{\Gamma^2\left(\frac{\alpha+1}{\alpha}\right)}\right] = \frac{Var[x]}{E^2[x]} - 1 \quad \text{solve for } \alpha \tag{12}$$

The ratio of gamma functions can be computed and stored in the form of a lookup table or chart as shown in FIG. 2. FIG. 2 is a chart of gamma functions as a function of Weibull parameters. Given the value of the ratio and the lookup table, the shape parameter can be determined.

The median parameter can then be calculated from the shape parameter.

$$x_m = \frac{E[x]\,(\ln 2)^{1/\alpha}}{\Gamma\left(\frac{\alpha+1}{\alpha}\right)} \tag{13}$$

Again, CFAR thresholds for Weibull clutter models have been determined for various detection strategies. For example, given the parameter of the Weibull clutter the optimal CFAR threshold of single pulse linear detection receiver can be computed as a function of the required probability of false alarm and the model parameters.

$$T = x_m\left[\frac{\ln(P_{fa}^{-1})}{\ln 2}\right]^{1/\alpha} = E[x]\,\frac{[\ln(P_{fa}^{-1})]^{1/\alpha}}{\Gamma[1+(1/\alpha)]} \tag{14}$$

The cell averaging CFAR threshold can be estimated from the clutter mean.

$$T = C(P_{fa},K,\alpha)E[x] = C(P_{fa},K,\alpha)\left(\frac{1}{K}\sum_{i=1}^{K} X_i\right). \tag{15}$$

The Weibull clutter threshold coefficient is again a complicated function of the probability of false alarm, the number of clutter samples used in estimating the mean, and the shape parameter. As the number of samples used in estimating the clutter mean increases, the threshold coefficient approaches it minimal value.

$$C(P_{fa},K,\alpha) \rightarrow \frac{[\ln(P_{fa}^{-1})]^{1/\alpha}}{\Gamma[1+(1/\alpha)]} \quad \text{as } K \rightarrow \infty \tag{16}$$

For both the lognormal and Weibull models knowledge of the clutter mean and variance completely characterizes the clutter through the calculated model parameter. In addition, knowing the model parameters allow a simple calculation of the CFAR threshold. Unfortunately, current cell averaging CFAR processor are only capable of estimating the clutter mean. In both cases, the shape parameters cannot be estimated from the clutter returns but are instead fixed and chosen to match the type of clutter from experience.

An ideal radar clutter modeling capability would consist of the instantaneous collection and processing of a substantial number of independent clutter radar cross section samples from the single resolution cell of interest and would allow the estimation of the clutter mean and variance. The estimated clutter mean and variance would allow the simple calculation of the two clutter model parameters through the solution of the simultaneous nonlinear equations previously given. The optimal CFAR threshold could then be calculated from the clutter model parameters.

Consider a monopulse collection of clutter radar cross section at a single radar frequency (FIG. 4). The monopulse collection of clutter samples requires only a homogeneous clutter model over the single resolution cell spanned by the four beams during a single radar pulse. The beamwidths and squint angles of the monopulse beams are set to eliminate any spatial dependence of the clutter response in the four beams comprising the monopulse (FIG. 5). The radar clutter in the four beams have the same clutter model and the samples from the four beams are independent. Each of the four beams in the monopulse returns a clutter radar cross section random variable with identical mean and variance

$$X_A, X_B, X_C, X_D\mu, \sigma^2. \tag{17}$$

Characteristic monopulse beam patterns within the radar resolution cell of interest are suggested in FIG. 7. The clutter returns from the four beam are shown as spatially separate (FIG. 7*a*). The spatial separation provided by the squint angle in amplitude monopulse tracking systems is adjusted to eliminate any statistical dependence in the clutter returns of the four beams. The clutter model is assumed to be homogeneous across the four beams comprising the sum and difference beam patterns (FIGS. 7*b*, 7*c*). The monopulse sum beam returns the clutter radar cross section random variable

$$X\Sigma = X_A + X_B + X_C + X_D. \tag{18}$$

The monopulse difference beam returns the clutter radar cross section random variable

$$X\Delta = X_A + X_B - X_C - X_D. \tag{19}$$

Now, the means of the sum beam and the squared difference beam are given as

$$\boxed{E[X_\Sigma] = 4\mu} \tag{20}$$

and

$$\boxed{E[X_\Delta^2] = 4\sigma^2} \tag{21}$$

These simple expression for the expected values of the clutter returns of the monopulse sum and difference beams

are significant in that they provide a method for simultaneously computing the mean and variance of the clutter model as

$$\mu=\frac{E[X_\Sigma]}{4} \tag{22}$$

and

$$\sigma^2=\frac{E[X_\Delta^2]}{4} \tag{23}$$

Now, if the radar clutter returns of the monopulse sum and difference beams could be collected and processed for a range of radar frequencies simultaneously, then the clutter model mean and variance could be estimated as

$$\mu \equiv \mu_{freq}=\frac{1}{4K}\sum_{i=1}^{K} X_\Sigma(f_i) \tag{24}$$

and

$$\sigma^2 \equiv \sigma^2_{freq}=\frac{1}{4K}\sum_{i=1}^{K} X_\Delta^2(f_i) \tag{25}$$

where f_i are the radar frequencies used in the K sample averages. The collection of clutter radar cross section samples through a range of radar frequencies is a standard technique utilized to ensure the samples are independent. The frequency variation causes the phase relationships within the distributed clutter to return independent radar cross section samples. The processing of the clutter returns of the monopulse sum and difference beams from a single frequency chirped pulse provides the K samples utilized in the simultaneous estimates of the clutter mean and variance.

The optical monopulse chirp processor is an architecture that implements the ideal clutter collection and processing capability identified in the previous section. The optical monopulse chirp processor requires only the sum and difference beam clutter cross section collected in the four beams of traditional monopulse tracking systems (FIG. 2). The clutter cross section returned in the four beams comprising the monopulse are inputs to optical spectrum analyzers. The optical spectrum analyzers function simply as convenient spatial frequency demultiplexors that allow parallel process of the frequency indexed clutter samples in the four beams from a single frequency chirped pulse. The optical implementation reduces the hardware requirements of the processor and allows for the practical utilization of a much larger number of frequency decorrelated clutter samples in estimating the clutter mean and variance. The collection of a large number of decorrelated clutter samples is required to legitimize using the simple asymptotic form of the threshold coefficients in the CFAR threshold calculation, equations 8 and 16. The two parameters of the clutter models and the CFAR thresholds can then be easily computed from the estimated clutter mean and variance.

The design and operation of optical spectrum analyzers in signal processing is presented in the above-cited patents. Optical spectrum analyzers are the most mature examples of optical signal processing technology. The details of their implementation as components of the optical monopulse chirp processor are known and modified as described above. The optical spectrum analyzers need only provide simultaneous magnitude measurement of an adequate number of frequency decorrelated clutter radar cross section samples. As such, the frequency accuracy of the collected clutter samples and the frequency resolution of the spectrum analyzers are not a primary concern. Consequentially, the detector arrays require only a third the number of elements needed in spectrum analysis. In addition, the fine alignment of the detector array to the spatial frequencies required for accurate frequency measurement is unnecessary. The optical monopulse chirp processor is tolerant of spatial frequency/detector array alignment and could therefore operate in demanding environments. The optical spectrum analyzers require only a total frequency bandwidth consistent with demultiplexing the monopulse chirp clutter returns onto the detector array. In practice, the dynamic range of power spectrum analyzers are generally limited to 40 dB. A dynamic range of over 80 dB is achievable with heterodyne spectrum analyzers. Linear detector arrays consisting of 4096 elements are readily available and acousto-optic cell with time-bandwidth products of 1000–3000 are typical. The number of samples scanned by a chirp of bandwidth W is on the order of the time bandwidth product of the acousto-optic cell.

The power of the monopulse chirp must be calibrated with the radar pulse of the search and/or tracking radar for the correct estimation of the CFAR threshold (FIG. 5). The pulse width of the search/tracking radar is τ and the frequency of the pulse is f_c. If the clutter mean and variance are to be estimated from K frequency demultiplexed samples from a frequency chirped monopulse, then the chirp width in each of the four beams must be $K\tau_c$ where

$$\tau_c=\alpha\tau=\geqq\tau. \tag{26}$$

The frequency chirp is centered on the search/tracking radar pulse frequency. The demultiplexed τ_c sections of the chirp will return independent clutter samples if adjacent sections maintain a frequency separation greater than $1/2\tau_c$. The sections of the chirp are centered on

$$f_i=f_a+\left(i+\frac{1}{2}\right)\frac{1}{2\tau_c}\quad i=1,2,3\ldots K. \tag{27}$$

The required bandwidth of the chirp is

$$W=f_b-f_a=(K+1)\frac{1}{2\tau_c}=(K+1)\frac{1}{2\alpha\tau} \tag{28}$$

The frequency requirements of the chirp can be traded against the chip width to accommodate the capabilities of the search/tracking radar.

FIGS. 8 and 9 are detailed illustrations of an optical monopulse chirp processor used with radar systems respectively for power spectrum analyzer implementation and heterodyne spectrum analyzer implementation.

The first implementation utilizes optical power spectrum analyzers as spatial frequency demultiplexors (FIG. 8). Power spectrum analyzers are the simplest to implement. The power spectrum analyzers provide the square of the clutter returns as outputs from its photodetector array, 802. The power spectrum analyzer implementation requires that the square roots of the digitized clutter samples be computed. The second optical implementation of the monopulse chirp processor utilizes heterodynes spectrum analyzers as spatial frequency demultiplexors (FIG. 9). The heterodyne implementation provides significantly greater dynamic range in processing clutter radar cross section returns. The heterodyne spectrum analyzers provide the magnitude of the clutter returns as outputs from its photodetector arrays. The analog outputs of the power and heterodyne spectrum analyzers are converted to digital format prior to squaring the difference beam samples and averaging the sum and difference beam returns. The average of the clutter causes the phase relationships within the distributed clutter to return independent radar cross section samples. The processing of the clutter returns of the monopulse sum and difference

beams from a single frequency chirped pulse provides the K samples utilized in the simultaneous estimates of the clutter mean and variance.

The optical monopulse chirp processor is an architecture that implements the ideal clutter collection and processing capability identified in the previous section. The optical monopulse chirp processor requires only the sum and difference beam clutter cross section collected in the four beams of traditional monopulse tracking systems (FIG. 2). The clutter cross section returned in the four beams comprising the monopulse are inputs to optical spectrum analyzers. The optical spectrum analyzers function simply as convenient spatial frequency demultiplexors that allow parallel processing of the frequency indexed clutter samples in the four beams from a single frequency chirped pulse. The optical implementation reduces the hardware requirements of the processor and allows for the practical utilization of a much larger number of frequency decorrelated clutter samples in estimating the clutter mean and variance. The collection of a large number of decorrelated clutter samples is required to legitimize using the simple asymptotic form of the threshold coefficients in the CFAR threshold calculation, equations 8 and 16. The two parameters of the clutter models and the CFAR thresholds can then be easily computed from the estimated clutter mean and variance.

The design and operation of optical spectrum analyzers in signal processing is presented in the above-cited patents. Optical spectrum analyzers are the most mature examples of optical signal processing technology. The details of their implementation as components of the optical monopulse chirp processor are known and modified as described above. The optical monopulse chirp processor of FIG. 8 is divided into two major sections: the power spectrum analyzer section, and the digital processor section. The power spectrum analyzer section consists of the spatial frequency is composed of:

a spatial frequency demultiplexor **801**, and a four element photodetector array **802**. The special purpose processor is composed of: an A/D converter **803**, a square root calculator **804**, an averaging calculator **806**, a combiner unit **805**, a parameter memory unit **807**, and a threshold calculator unit **890**. The components of the CFAR processor may be implemented in a conventional CFAR processor (when modified by the teachings of the present invention) or in individual electronic components. In operation, the power spectrum analyzer receives sum and difference beam clutter cross sections collected from at least four beams of a phased array radar antenna and receiver system. The power spectrum analyzer outputs four electric signals that represent the square of the clutter returns using the spatial frequency demultiplexor **801** (which separates and processes the four beams in parallel) and the four element sensor array **802** (which converts the four optical output beams of the spatial frequency demultiplexor into their four equivalent transverse electrical signals by photodetecting received optical beams.

The A/D converter **803** outputs four digital data streams by processing the four electrical signals from the sensor array. The square root calculator **804** calculates the square root of each of these four digital data streams to produce thereby four digital clutter return measurement signals. The beam combiner **805** combines the four digital clutter return measurement signals for averaging and CFAR detection threshold calculation as described in the above-cited patent of Mary Wolf.

As described in the Wolf patent: once the X average clutter value is known, for a Rayleigh distribution estimate of threshold is given by:

$$T=(-LNP)^{1/2}\cdot\frac{2X}{\sqrt{\pi}}.$$

If the distribution is Weibull,

$$T=b-\frac{(LNP)}{a}.$$

The selection of which estimation method is desired is implemented by the parameter memory unit **807** and CFAR processor **890**.

The systems of FIGS. **8** and **9** use many common elements as described by the following U.S. Patents for Optical spectrum analyzer systems, the disclosures of which are incorporated herein by reference:

U.S. Pat. No. 5,412,469 issued to Squillman;
U.S. Pat. No. 5,233,405 issued to Wildnaner et al;
U.S. Pat. No. 5,066,126 issued to Hatori;
U.S. Pat. No. 4,464,624 issued to Osterwalder;
U.S. Pat. No. 3,883,803 issued to Burns et al; and
U.S. Pat. No. 3,636,255 issued to Gaddy et al.

In FIG. **8**, the spatial frequency demultiplexor **801** processes the four beams (A, B and C) received by the four radar elements of FIG. **2** to produce four optical beams for a sensor array **802**. In other words, every radar element in a phased array radar system will have its received signal processed separately by the spatial frequency demultiplexor and a separate photodetector element in a sensor array **802**.

As mentioned above, the power spectrum analyzer provides the square of the clutter returns as outputs from its photodetector arrays. The power spectrum analyzer implementation requires that the square roots of the digitized clutter samples be computed. This is accomplished by converting the output of the sensor array **802** into a digital signal, using the A/D converter **803**, and then using a unit **804** to calculate the square root. The beams are then combined by the combiner **805** and averaged **806** for CFAR detection threshold calculation as described above.

In the system of FIG. **9**, the optical implementation of the monopulse chirp processor utilizes a heterodynes spectrum analyzer as a spatial frequency demultiplexor **901**. The heterodyne implementation provides significantly greater dynamic range in processing clutter radar cross section returns. The heterodyne spectrum analyzers provide the magnitude of the clutter returns as outputs from its photodetector arrays. The analog outputs of the power and heterodyne spectrum analyzers are converted to digital format **803** prior to squaring the difference beam samples and averaging **806** the sum and difference beam returns. The optical spectrum analyzers need radar cross section returns of the sum and difference beams for either implementation are given as

$$\frac{\tau}{4\tau_c K}\sum_{i=1}^{K} X_\Sigma(f_i)\equiv\mu \tag{29}$$

and

$$\frac{\tau^2}{4\tau_c^2 K}\sum_{i=1}^{K} X_\Delta^2(f_i)\equiv\sigma^2. \tag{30}$$

The averages are calibrated to accommodate the utilized radar pulse and chirp widths. The illustrations of the optical monopulse chirp processor utilizes arrays in the microprocessor to suggest the possibilities for parallel implementations of the computations after the A/D converters. The electronic computations involved in the clutter mean and variance estimation could be sequentially implemented and accumulated for averaging.

The clutter mean and variance estimates from either implementation are supplied to the clutter model parameter and CFAR threshold solver. The clutter model parameters and CFAR thresholds are determined using equations 4, 5 and 6 for the lognormal model or equations 12, 13 and 14 for the Weibull model.

Real-time two-parameter radar clutter modeling is now practical in radar remote sensing and target detection environments. Two optical implementations of the monopulse chirp processor have been presented that provide for the real-time estimation of the clutter variance as well as the clutter mean. The estimated clutter mean and variance allow the calculation of both lognormal and Weibull clutter model parameters. The determination of the clutter model parameters allow the simple calculation of CFAR receiver threshold for a wide variety of detection strategies. The monopulse scheme collects clutter samples from the single radar resolution cell of interest thereby eliminating clutter model edge effects and large discrete interference associated with current cell averaging CFAR processors. The requirement of a homogeneous clutter model over a single resolution cell during a single chirped radar pulse is a more realistic condition than the homogeneous clutter window requirements of current cell averaging CFAR processors. The optical monopulse chirp processor could be easily integrated into existing traditional monopulse tracking and modern multiple beam forming phased array systems.

The current implementations of the optical monopulse chirp processor are designed to operating within a target free radar resolution cell. Strategies for modifying the optical monopulse chirp processor architecture to accommodate clutter model parameter and CFAR threshold estimation with a target present within the radar resolution cell are currently under investigation. In addition, the optical monopulse chirp processor has direct application for clutter modeling and CFAR threshold determination within analogous chirped monopulse sonar environments.

While the invention has been described in its presently preferred embodiment it is understood that the words which have been used are words of description rather than words of limitation and that changes within the purview of the appended claims may be made without departing from the scope and spirit of the invention in its broader aspects.

What is claimed is:

1. An optical processor system for use with a phased array radar system for calculating a detection threshold using radar echo return signals which contain clutter components from at least four antenna elements of said phased array radar system, wherein said optical processor system comprises:

a power spectrum analyzer unit which receives and processes the radar echo return signals of said antenna elements of said phased array radar system to output thereby a set of transverse electric signals that represent a square of the clutter components of the radar echo return signals; and

a means for digitally calculating a detection threshold from the set of transverse electric signals produced by the power spectrum analyzer.

2. An optical processor system, as defined in claim 1, wherein said power spectrum analyzer unit comprises:

a spatial frequency multiplexor unit which receives and processes the radar echo return signals of said antenna elements to output thereby a set of optical beams which each represent the square of the clutter component received by a single antenna element; and

a set of optical photodetectors in a sensor array which photoelectrically convert said set of optical beams into said set of transverse electric signals for said digitally calculating means.

3. An optical processor system, as defined in claim 1, wherein said means for digitally calculating said detection threshold comprises:

a means for converting said set of transverse electric signals from said power spectrum analyzer unit into discrete sets of digital data streams;

a means for deriving a set of digital clutter measurement signals from said discrete set of digital data streams from said converting means;

a means for combining said set of digital clutter measurement signals from said deriving means into a combined clutter measurement signal;

a means for producing an average clutter measurement signal from the combined clutter measurement signal; and

a CFAR digital processor system which calculates said detection threshold from said average clutter measurement signal from said producing means.

4. An optical processor system, as defined in claim 2, wherein said means for digitally calculating said detection threshold comprises:

a means for converting said set of transverse electric signals from said power spectrum analyzer unit into discrete sets of digital data streams;

a means for combining said set of digital clutter measurement signals from said deriving means into a combined clutter measurement signal;

a means for producing an average clutter measurement signal from the combined clutter measurement signal; and

a CFAR digital processor system which calculates said detection threshold from said average clutter measurement signal from said producing means.

5. An optical processor system, as defined in claim 3, wherein said CFAR digital processor system comprises:

a memory means which is capable of producing an output signal by storing and outputting said average clutter measurement signal from said producing means along with a set of detection threshold formulas for calculating said detection threshold with Raleigh distribution and with Weibull distribution; and

a microprocessor element which calculates and outputs the detection threshold using the output signal of said memory means.

6. An optical processor system, as defined in claim 4, wherein said CFAR digital processor system comprises:

a memory means which is capable of producing an output signal by storing and outputting said average clutter measurement signal from said producing means along with a set of detection threshold formulas for calculating said detection threshold with Raleigh distribution and with Weibull distribution; and

a microprocessor element which calculates and outputs the detection threshold using the output signal of said memory means.

7. An optical processor system for use with a phased array radar system for calculating a detection threshold using radar echo return signals which contain clutter components from at least four antenna elements of said phased array radar system, wherein said optical processor system comprises:

a heterodyne spectrum analyzer unit which receives and processes the radar echo return signals of said antenna

elements of said phased array radar system to output thereby a set of transverse electric signals that represent a magnitude of the clutter components of the radar echo return signals: and

a means for digitally calculating a detection threshold from the set of transverse electric signals produced by the heterodyne spectrum analyzer.

8. An optical processor system, as defined in claim 7, wherein said heterodyne spectrum analyzer unit comprises:

a spatial frequency multiplexor unit which receives and processes the radar echo return signals of said antenna elements to output thereby a set of optical beams which each represent the magnitude of the clutter component received by a single antenna element: and

a set of optical photodetectors in a sensor array which photoelectrically convert said set of optical beams into said set of transverse electric signals for said digitally calculating means.

9. An optical processor system, as defined in claim 7, wherein said means for digitally calculating said detection threshold comprises:

a means for converting said set of transverse electric signals from said heterodyne spectrum analyzer unit into discrete sets of digital data streams;

a means for combining said discrete set of digital data streams clutter measurement signals from said converting means into a combined clutter measurement signal;

a means for producing an average clutter measurement signal from the combined clutter measurement signal: and

a CFAR digital processor system which calculates said detection threshold from said average clutter measurement signal from said producing means.

10. An optical processor system, as defined in claim 8, wherein said means for digitally calculating said detection threshold comprises:

a means for converting said set of transverse electric signals from said heterodyne spectrum analyzer unit into discrete sets of digital data streams;

a means for combining said discrete set of digital data stream clutter measurement signals from said converting means into a combined clutter measurement signal;

a means for producing an average clutter measurement signal from the combined clutter measurement signal; and

a CFAR digital processor system which calculates said detection threshold from said average clutter measurement signal from said producing means.

11. An optical processor system, as defined in claim 9, wherein said CFAR digital processor system comprises:

a memory means which is capable of producing an output signal by storing and outputting said average clutter measurement signal from said producing means along with a set of detection threshold formulas for calculating said detection threshold with Ralcigh distribution and with Weibull distribution: and

a microprocessor element which calculates and outputs the detection threshold using the output signal of said memory means.

12. An optical processor system, as defined in claim 10, wherein said CFAR digital processor system comprises:

a memory means which is capable of producing an output signal by storing and outputting said average clutter measurement signal from said producing means along with a set of detection threshold formulas for calculating said detection threshold with Raleigh distribution and with Weibull distribution: and

a microprocessor element which calculates and outputs the detection threshold using the output signal of said memory means.

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